Nitrogen fertigation: An integrated agronomic and environmental study

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A B S T R A C T

Proper management of the N applied to crops is necessary in order to increase yield, improve water use efficiency (*WUE*) and reduce the pollutions risks with the least economic, environmental and health costs. A field study with melon crops was conducted during 2005, 2006 and 2007 in central Spain, using 11 different amounts of N. Some environmental indexes have been proposed, to provide an essential tool for determining the groundwater pollution risks associated with common agricultural practices. These indexes are related to variation in the nitrate concentration of drinking water (Impact Index (*II*)) and groundwater (Environmental Impact Index (*EII*)). Also, the Management Efficiency (*ME*) was calculated, which is related to the amount of fruit produced per gram of N leached (N_l). To determine the optimum dose of N, it was also necessary to know the N mineralisation (*NM*). Our results show that 160 kg ha^{-1} of available N (N_{av}) produced the maximum fruit yield (*FY*), enhanced *WUE* and gave an *NM* of 85 kg ha^{-1}, while the impact indexes did not exceed the fixed maximum allowable limits and *ME* was adequate. The proposed indexes proved to be an effective tool for determining the risk of nitrate contamination and confirmed that the optimum dose of N corresponded to the maximum *FY* with minimal loss of N_l.

1. Introduction

Best management practices (BMP) are needed for much of the cropped, irrigated and fertigated land in Spain, to avoid contamination of fresh water and groundwater. Spain is the world's fifth-largest producer of melon: approximately one-third of its annual production is exported, making it the world's largest exporter (FAOSTAT, 2009). Sixty-seven per cent of the area under melon cultivation in Spain is fertigated and plastic-mulched (MARM, 2009). Plastic mulches have numerous advantages, such as reduction in the evaporation losses from bare soil (Lovelli et al., 2005). Principally, melon is cultivated in vulnerable zones to nitrate pollution in the centre of Spain (Directive 91/676/CEE).

Recent irrigation research on melon crops in this area has followed the farmers' needs, trying to give answers to their concerns regarding water supply, irrigation systems and the homogeneity and efficiency of water distribution (Ortega et al., 2005; Ribas et al., 1995). However, if the irrigation water has high salinity, in order to avoid salt accumulation in the soil and prevent yield loss, salts in the soil must be controlled, so it is necessary to increase the volume of water applied in order to wash out soil salts, named "leaching fraction", that accumulate, mainly with drip systems (Doorenbos and Pruitt, 1977; Ayers and Westcott, 1987), resulting in nitrate leaching. The salinity will increase in the root zone if this practice is avoided, limiting crop development due to decreased photosynthetic activity (Chartzoulakis, 1994; Nakamura et al., 2004). The amount of water used for this purpose depends on its salt concentration and on crop tolerance. Melon is moderately sensitive to salinity (100% crop loss at water E.C. > 16 dS/m) (Ayers and Westcott, 1987).

Little information is available on the influence of N fertiliser on melon crop development, and even large amounts of N are used by growers. The maximum limit of N fertilisation given by the administration is 110 or 135 kg ha^{-1} in the vulnerable zones, according to the zone of application (DOCM N° 73, 2001). But, if the N content of the irrigation water is considered in these zones, which could be around 150 mg L^{-1}, or even higher (IGME, 1985), then, with the fertiliser, the total N applied exceeds 250 kg ha^{-1}.

A fertiliser dose higher than the crop needs creates a scenario where nitrate leaching to the aquifer and its resulting contaminating are highly probable (Bawatharani et al., 2004; Oenema et al., 2005) and are accompanied by an increased soil concentration of nitrate (Poch et al., 2005). This situation is particularly likely to arise in this area, since soil depth is not more than 0.60 m and semi-arid conditions prevail during the crop season. Good water and fertiliser management is imperative, as in other areas (Moreno et al., 1996; Eilers et al., 2007).

This aspect is highly important in the periods between crops, during which precipitation leaches soil nitrate. This has two negative effects: nitrate is lost for the next crop and nitrate concentration increases in the aquifers (Cartagena et al., 1995; Casey et al., 2002). These aquifers are the main sources of water supply to the human population and nitrate contamination can cause health problems (Niaz et al., 2004). The objective of BMP is a rational N fertilisation that minimises the environmental impact and maximises yield (Bilbao et al., 2004; Derby et al., 2005).

The nitrate leaching is strongly related to soil water content, soil texture and available nitrate concentration (He et al., 2011). Excessive doses of N and/or water applied to fertigated crops involve a substantial risk of aquifer contamination by nitrate; knowledge of N cycling and availability within the soil could assist in avoiding this excess. Strategies are being sought that increase water use efficiency in cropping systems and reduce drainage (*D*). Estimation of the N mineralised from soil organic matter is essential to determine the amount necessary to optimise crop yield and minimise the environmental impact of excess N.

The aim of this work was to study N management in fertigation, considering two fundamental aspects – economic and environmental – that condition the optimum fertiliser dose. This requires an integrated optimisation of both aspects. From an economic standpoint, we require maximum yield with minimum water and fertiliser consumption. The environmental aspect refers to minimum loss of leachate and maximum utilisation of soil N, which implies mobilisation of the different N species in it. The results of this study will provide a guideline to growers and agencies regarding optimum water and N fertiliser management for fertigated crop systems.

2. Efficiencies and indexes applied

The optimum N dose can be calculated from the indexes and efficiencies shown in this work – these can be classified into four groups: water use efficiencies (*WUE*, *IRRWUE*, *DWUE* and *DIRRWUE*), environmental impact indexes (*II*, *EII* and *ME*), soil N mobilisation (*NM* and *NMI*) and N use ($N_{up}E$) (Fig. 1).

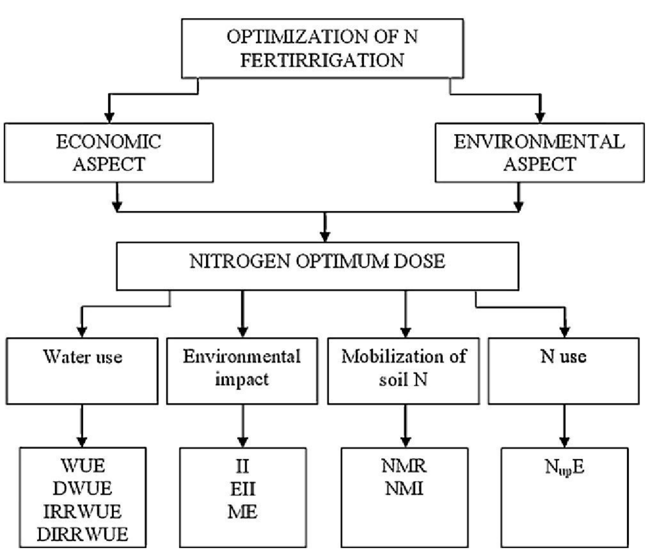

Fig. 1. Chart describing the optimisation of N fertirrigation, in economic and environmental terms.

The water use efficiency (*WUE*) is the ratio between the yield and the water used to get this yield. Normally, the highest yield is achieved with a complete restitution of crop evapotranspiration (*ETc*), although *WUE* decreases with an increase in irrigation. In this work we will refer to fruit yield (*FY*) and dry weight (*DW*). To estimate the water spent in the crop season, *ETc* is used, as estimated to evaluate the irrigation. Based on this estimation, the calculated efficiencies are:

$$WUE = \frac{FY}{ETc}; \qquad DWUE = \frac{DW}{ETc} \tag{1}$$

The irrigation system affects the homogeneity and the amount of water that finally is available to the crop. *IRRWUE* decreases with an increase in irrigation water (*Irr*). Based on this, the calculated efficiencies are:

$$IRRWUE = \frac{FY}{Irr}; \qquad DIRRWUE = \frac{DW}{Irr} \tag{2}$$

In some cases, *IRRWUE* is also calculated as the ratio of yield increase to irrigation plus precipitation (*P*). In this study, *P* was negligible. In addition, the high salt content of the irrigation water necessitates increasing the volume of water applied to wash out the so-called leaching fraction or salt deposited in the soil, primarily by drip systems (Doorenbos and Pruitt, 1977; Ayers and Westcott, 1987).

The shortage of water resources of good quality is becoming an important issue in the arid and semi-arid zones. It is very important not to alter too much, without good reason, the irrigation water quality. Irrigation return flows with water of poor quality are a pollution source for the surface water and the groundwater (Beltrán, 1999).

Many areas in Spain have groundwater nitrate concentrations much higher than the European limit established by the Drinking Water Directive (DWD). This problem is aggravated because, besides being used for irrigation, groundwater is also one of the main sources of drinking water; about 30% of the population is supplied by groundwater (Miner-Moptma, 1994). Consequently, it is necessary to protect the groundwater against nitrate pollution, as consequence of agricultural practices. In a study in Western Europe, the nitrate in the annual groundwater recharge showed rather-high mean concentrations for sandy soils with arable crops, intensively managed and grazed grassland and field crops of vegetables, which could exceed the limit established by the DWD (Strebel et al., 1989).

The intensive use of N in agricultural systems has negatively impacted on environmental quality, due to the use of more fertiliser than is needed by the crop result in nitrate leaching into aquifers and, at the same time, the significant amount of N remaining in the soil, resulting in a time of intercropping nitrates leaching with *P*. Correct N management, to reduce the pollution risk, may lead to higher production with the minimum economic and environmental cost. With this purpose, several environmental indexes were defined based on the N leaching arising from the agricultural practices. These indexes must be defined in nitrate concentration terms, according to the contamination directives.

The first index considered, the Impact Index (*II*), was designed to show whether the leached nitrate exceeded the maximum nitrate concentration considered by the DWD, which establishes a maximum allowable level of 50 mg L^{-1}. It is expressed as the ratio between the concentration of nitrate in the leachate ($Nitrate_{leachate}$) and the threshold concentration of the DWD:

$$II = \frac{Nitrate_{leachate}}{50} \tag{3}$$

The second index shows how agricultural practices affect the quality of the groundwater, being named the Environmental Impact Index (*EII*):

$$EII = \frac{Nitrate_{leachate}}{Nitrate_g} \quad (4)$$

where $Nitrate_g$ is the nitrate concentration in groundwater. In a greenhouse study (Muhammetoglu et al., 2005), the ratio $N_{leachate}/N_{groundwater}$ was measured and depended, among other factors, on the amount of N excess, so it helps establish the basic parameters of irrigation and fertiliser application required to minimise the groundwater pollution.

As far as we know, there has not been any attempt in a field study to consider both the economic and environmental aspects in a unique index. Therefore, we have tried to do so with the Management Efficiency (*ME*), defined as:

$$ME = \frac{FY}{N_l} \quad (5)$$

where *FY* is the fruit yield and N_l is the amount of N leached.

To determine the N application that maximises yield and minimises nitrate leaching, knowledge of the N available (N_{av}) is necessary. Besides the available soil N and the N applied (N_{ap}), this also requires knowledge of the N mineralised following the application. Methods to estimate the amount of N mineralised from soil organic matter are needed for accurate fertiliser recommendations which avoid excessive applications and the risks of nitrate pollution. The N mineralised in the soil may be an important source of N for crop nutrition. In this study, the N mineralisation (*NM*) was calculated from the N balance:

$$NM = N_{up} + N_l + N_s\ final + N_g - N_{ap} - N_s\ initial \quad (6)$$

where N_{up} is the N uptake by the plant, N_s *final* is the mineral N in the soil at the end of the crop, N_g is the N loss by denitrification (this parameter was considered negligible in our experimental conditions (Sánchez-Martín et al., 2008), N_{ap} is the N applied (the sum of the N in the irrigation water (N_w) and in the N fertiliser (N_f)) and N_s *initial* is the mineral N in the soil before transplanting the melon plants. The sum of N_{ap} and N_s *initial* is the N available (N_{av}), so that Eq. (6) becomes:

$$NM = N_{up} + N_l + N_s\ final - N_{av} \quad (7)$$

To reflect the variation of *NM* as a function of N_{av}, a ratio between the two parameters was defined, namely the N Mineralisation Index (*NMI*):

$$NMI = \frac{NM}{N_{av}} \quad (8)$$

In the balance, if N_{av} and *NM* are considered as N sources, and N_{up} as the only N sink, the difference between the sources and sink could give an idea of the excess N, of which a part will be leached (N_l) while the rest will remain in the soil (N_s *final*). So, it will be useful to know the amount of available (N_{av} + *NM*) that is taken up by the melon crop. This is called the N uptake efficiency ($N_{up}E$), defined as:

$$N_{up}E = \frac{N_{up}}{N_{av} + NM} \quad (9)$$

3. Materials and methods

3.1. Experimental design

Field trials were carried out at the *La Entresierra* field station at Ciudad Real in central Spain (3°56′ W; 39°0′ N; 640 m altitude), during the May–September season of 2005, 2006 and 2007. The study area presents a plain landscape. The soil is a shallow sandy-loam, moderately basic (7.9 pH), medium in organic matter (22 g kg^{-1}) and rich in potassium (342–399 mg kg^{-1}). It is classified as Petrocalcic Palexeralfs (Soil Survey Staff, 2010), with a depth between 0.60 and 0.70 m, below which there is a discontinuous and fragmented petrocalcic horizon. The soil is very permeable above the petrocalcic horizon. Its genetic horizons are: Ap (0–0.3 m), Btk (0.3–0.6 m), Ckm (0.6–1.0 m), Cck (1.0 to >1.5 m). Fissures within the petrocalcic horizon provide higher vertical permeability locally. The depth to groundwater is approximately 20 m.

Table 1
The physicochemical properties of the irrigation water used in the experiment in 2005, 2006 and 2007.

Properties	2005	2006	2007
pH	7.9	7.9	8.2
EC (dS m^{-1})	2.0	2.5	0.3
NO_3^- (mg L^{-1})	5.6	80.6	10.9
NH_4^+ (mg L^{-1})	0.1	0.1	0.1
SO_4^{2-} (mg L^{-1})	790.7	1376.5	56.1
K^+ (mg L^{-1})	1.4	3.6	2.5
Mg^{2+} (mg L^{-1})	16.5	176.0	10.9
Na^+ (mg L^{-1})	163.3	138.0	17.5
Ca^{2+} (mg L^{-1})	193.1	323.3	34.8
Cl^- (mg L^{-1})	240.1	185.8	44.5

The volumetric water content for the first 0.3 m was 22.8% at field capacity (soil matric potential of −0.03 MPa) and 12.1% at wilting point (soil matric potential of −1.5 MPa) and from 0.3 to 0.7 m it was 43.0 and 21.1%, respectively.

The area is characterised by a continental Mediterranean climate, with widely fluctuating daily temperatures and with an average annual rainfall of 400 mm, mostly distributed outside the melon growing period. The total reference evapotranspiration (*ETo*) over the crop cycle ranged from 638.2 to 690.5 mm.

During the three years previous to the experiment, the plots did not receive any organic or fertiliser amendments and were used to grow non-irrigated winter wheat (*Triticum aestivum* L.).

Due to low rainfall during the months of melon crop and high evapotranspiration rates, irrigation is necessary, but given the salinity of irrigation water and percolation water loss, uncontrollable, out of the reach roots due to soil texture, applying a higher amount of water to the crop needs is necessary to wash the accumulation of salts in the soil and does not affect to the crop, so that drainage occurs (Doorenbos and Pruitt, 1977; Ayers and Westcott, 1987).

The irrigation water quality was measured weekly (Table 1). In 2005 and 2007, surface water was used, from a reservoir near the experimental field, in order to apply a treatment with the least amount of N. In 2006, the water used was groundwater from a well near the experimental plots, since it was not possible to use the water source of the previous year.

The type of melon cultivated most in Spain is the "piel de sapo"; we selected the hybrid "Sancho" (*Cucumis melo* L. cv. Sancho) since it is the main one used by local farmers. Melon seeds were germinated in a greenhouse in April of all three years, until they had sprouted two or three real leaves. Subsequently, they were transplanted (26 May 2005, 24 May 2006 and 28 May 2007) onto plastic mulch at a density of 4444 plants ha^{-1} (1.5 m × 1.5 m). A randomised complete-block design was used, with four N treatments in 2005 and 2007 and three in 2006. Each treatment was replicated four times in plots measuring 10.5 m × 12 m. Each plot consisted of seven rows with eight plants each and a drip-irrigation system with emitters every 0.5 m, providing 2 L h^{-1}.

In all three years, the plots were fertilised with 120 kg ha^{-1} of phosphorus fertiliser (phosphoric acid), added to the irrigation water and injected daily, from three weeks after transplanting until the last week of August. A regular programme of disease and insect control was followed throughout the growing period, according to standard management practices, so that the response to N would not be obscured by other factors.

3.2. Crop yield parameters

The plots were harvested when there was a significant number of ripe fruit in the field. The weekly total *FY* was determined. Nitrogen production functions were obtained by relating the *relative FY* (*FY/maximum FY*) to the N_{av}.

Four plants per treatment were harvested in each plot at 91, 83 and 92 days after transplanting (DAT) in 2005, 2006 and 2007, respectively. Sampling was performed so as to avoid border effects.

The blades, petioles, stems and fruits, including ripe fruits, were separated and weighed to obtain the fresh weight. The dry weights of these separated organs were determined following oven-drying at 80 °C to constant weight. The *DW* was determined as the sum of the dry weights of the above-ground plant organs.

3.3. Nitrogen parameters

3.3.1. Nitrogen applied and Nitrogen available

We use here the term N_{ap} as the sum of N_f and N_w (measured weekly). The N_f was applied in the form of ammonium nitrate over 10 weeks of the crop cycle (from June to August), from a single well at one end of the field where irrigation water was mixed with the respective doses. The N_{ap} were 30, 85, 112 and 139 kg ha^{-1} in 2005; 93, 243 and 393 kg ha^{-1} in 2006 and 11, 61, 95 and 148 kg ha^{-1} in 2007.

The N_s was determined from samples taken at 0.20 m intervals to a depth of 0.60 m. The samples were extracted with 1 M KCl (20 g of soil: 100 mL of KCl), centrifuged, and stored in a freezer for subsequent analysis. The nitrate concentration in the extracts was determined with an ion-selective electrode and the ammonium concentration using spectrophometric techniques.

Thus, considering the N_{av}, the treatments were: 122 (N_{122}), 176 (N_{176}), 200 (N_{200}) and 219 (N_{219}) kg ha^{-1} in 2005; 156 (N_{156}), 314 (N_{314}) and 461 (N_{461}) kg ha^{-1} in 2006 and 47 (N_{47}), 91 (N_{91}), 124 (N_{124}) and 188 (N_{188}) kg ha^{-1} in 2007.

3.3.2. Nitrogen uptake

Sub-samples of the oven-dried, above-ground plant organs (blades, petioles, stems and fruits) were ground to a fine powder for the determination of the N content, using the Kjeldahl method (Association of Official Analytical Chemists, 1990). The N accumulated by each organ was obtained as the product of N concentration and biomass. The N_{up} was determined as the sum of the N accumulations of each above-ground organ of the plant.

3.4. Irrigation, drainage and water use

In order to facilitate the crop establishment, all plots received 30 mm of water. The irrigation schedule was calculated from 12 to 104 DAT in 2005, from 15 to 105 DAT in 2006, and from 23 to 100 DAT in 2007, as a single, daily irrigation of 100% *ETc*. The *ETc* was calculated daily as $ETc = Kc \times ETo$ (FAO method) (Doorenbos and Pruitt, 1977); *Kc*, the crop coefficient used, was obtained in the same area for melon under plastic mulch (Ribas et al., 1995) and *ETo* is the reference evapotranspiration calculated by the FAO Penman–Monteith method (Allen et al., 2002). The rainfall was negligible, so the water applied was calculated as the ratio between the *ETc* of the previous week and the efficiency of the system, estimated as 0.81 using the methodology of Rincón and Giménez (1989). This result, called theoretical irrigation (irrigation calculated), was divided by the number of days to obtain the daily irrigation requirements. The real irrigation was the amount of water registered on the water meter (irrigation applied).

To estimate *D*, measurements were taken at different distances from the drip line. Three tubes were installed in the centre of every plot and between two consecutives plants to measure the volumetric soil water content (θ_v) on a weekly basis, in a straight line at 12.5, 37.5 and 62.5 cm from the drip line, with a probe (Diviner 2000) based on FDR (Frequency Domain Resonance). The *D* for each treatment was calculated according to the water balance approach $D = Irr + P - ETc - Rf \pm \Delta\theta_v$ (Doorenbos and Pruitt, 1977). The runoff (*Rf*) was assumed to be negligible.

3.5. Nitrogen leaching

A porous ceramic cup was installed at 0.60 m depth and 32.5 cm from the irrigation line for each plot, to obtain weekly samples of the soil solution (a suction of −0.7 bar was applied to the porous ceramic cups to extract water), simultaneously with the FDR measurements. The nitrate concentration in the soil solution was measured with an ion-selective electrode. The N_l to below 0.60 m was calculated as the product of nitrate concentration and *D*. The average concentration of $Nitrate_{leachate}$ was calculated by dividing the amount of N_l by the total estimated *D* volume.

3.6. Statistical analysis

The data were analysed statistically using ANOVA. Because of differences in the treatments, the data for each year were submitted to ANOVA separately. Tukey's test was applied: treatment effects were considered significant at $p \le 0.05$. Linear and quadratic regressions were performed using the SPSS statistical analysis software.

4. Results and discussion

4.1. Crop production

The N_{av} had a clear effect on *FY* and *DW* (Fig. 2A and B). Considering all years, two linear regressions were obtained as a result of dividing the *relative FY* response to N_{av} into two intervals (47–181 and 181–461 kg ha^{-1}). The first straight line (1) is upward and shows the increase in *relative FY* as N_{av} increases from 41 to 181 kg ha^{-1}. The second straight line (2) is down-ward and shows the decrease of *relative FY* as N_{av} continues increasing up to 461 kg ha^{-1}. Yields above 95% of the maximum yield could be obtained with N_{av} amounts between 160 and 225 kg ha^{-1}.

It is known that as the N rate increases so does fruit yield up to a maximum value beyond which any increase in N rates leads to a corresponding yield decrease (Purqueiro et al., 2003; Kirnak et al., 2005). In the literature, the optimum N rate changes as a function of melon variety, climate, soil and other factors, although, while there are several studies for melon types other than Piel de Sapo and their results were not coincident.

The *DW* ranged between 6.0 and 10.2 t ha^{-1}: increasing the amount of N_{av} resulted in an increase of *DW*, except in 2006 – when no significant effect of N was found (Castellanos et al., 2010a). Nitrogen stimulates vegetative growth, while too much N can inhibit flowering and fruit production (Mills and Jones, 1979; Draggan, 2009).

4.2. Water parameters

The *ETc* was 472.8 mm in 2005, 419.5 mm in 2006 and 356.9 mm in 2007 (Fig. 3A–C). The *Irr*, considering the initial watering, was 604.2, 552.9 and 488.1 mm in 2005, 2006 and 2007, respectively (Fig. 3A–C). Throughout the irrigation period, *Irr* was much greater than *ETc*; this meant that there was *D*.

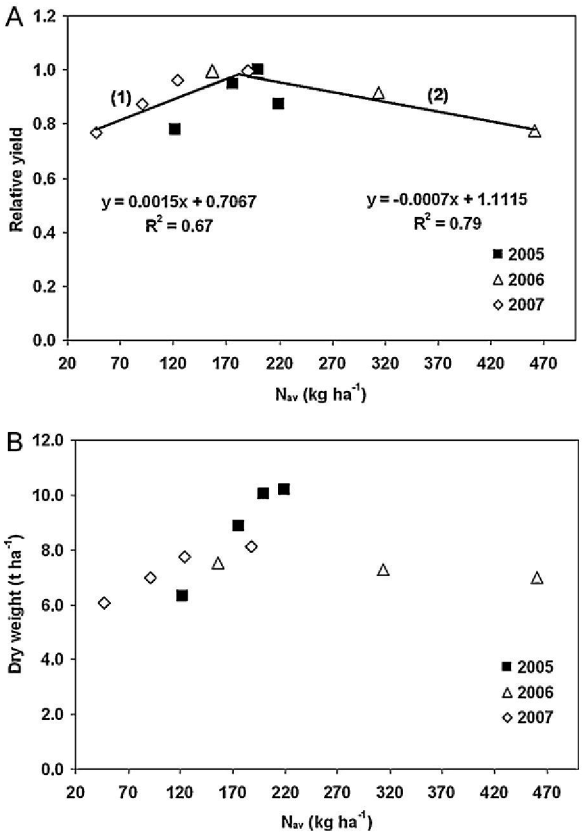

Fig. 2. Relative fruit yield versus N available (N_{av}) in 2005, 2006 and 2007 (A) and dry weight (*DW*) versus N_{av} in 2005, 2006 and 2007 (B).

The *D* showed a similar pattern in all three tubes (Castellanos et al., 2007): significant differences were not observed, which demonstrates the homogeneity of the moisture within the bulb. This could be due to the shallow soil (meaning that the water was distributed uniformly), its texture and the implementation of daily irrigation, resulting in constantly moist soil.

Considering all years, the *D* ranged from 62.8 mm to 97.9 mm, a water loss of 14% and 17% (considering the irrigation applied during the period in which the irrigation was scheduled, without the initial irrigation for crop establishment (30 mm)), respectively (Fig. 3A–C). In 2005, significant differences were found in the cumulative *D*: the D was higher in the two treatments with lower doses of N, while for the other two treatments with higher doses, the D was lower. Kirnak et al. (2005), in a study with fertirrigated muskmelon on raised bed covered with plastic mulch, reported that the drainage below 60 cm, after a number of soil-water content measurements, was considered to be negligible.

In a study of crop rotation with corn and soybean, significant differences in *D* due to N treatments, which ranged between 57 and 202 kg ha^{-1}, were not found (Jaynes et al., 2001). In a study with maize, *D* was lower in subplot where a high N-fertilisation rate was applied, than in subplot of the lower rate (Moreno et al., 1996).

4.3. Water use efficiencies

The N availability affected significantly the indexes related with the water use (Table 2). The highest values of *WUE* and *IRRWUE* were observed in treatments with greater *FY*. In 2005, the highest *WUE* and *IRRWUE* were obtained with 200 kg ha^{-1} of N_{av}, decreasing by 22% and 13% when the N availabilities were 122 and 219 kg ha^{-1}, respectively. In 2006, the highest *WUE* and

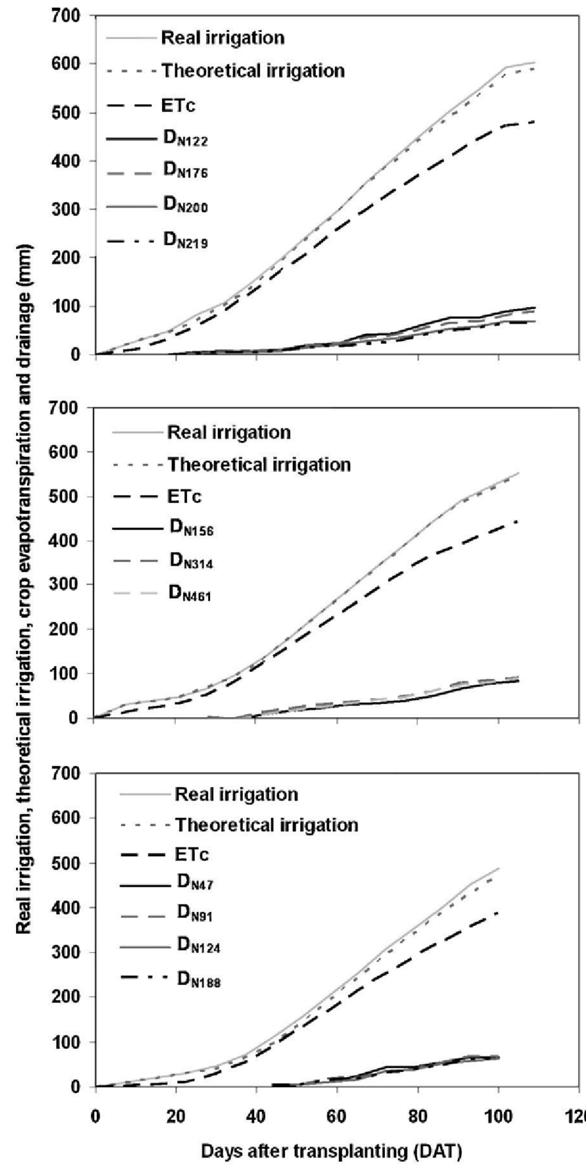

Fig. 3. Cumulative crop evapotranspiration (*ETc*), theoretical irrigation, real irrigation and drainage of each N treatment in 2005 (A), 2006 (B) and 2007 (C).

IRRWUE were achieved with 156 kg ha^{-1} of N_{av}, decreasing by 23% with 461 kg ha^{-1}. In 2007, N availabilities of 124 and 188 kg ha^{-1} increased by 25% and 30%, respectively, the efficiency obtained at 47 kg ha^{-1}.

The highest efficiencies were obtained with a N_{av} of 181 kg ha^{-1}, which obtained the maximum *FY*, and if this amount of N was increased, the efficiency was reduced, because the *FY* was reduced. However, efficiencies above 95% of the maximum value could be obtained at 160 kg ha^{-1}.

The *WUE* increased to its optimum value with a N_{ap} of 90 kg ha^{-1}, at which the melon *FY* was maximal (Cabello et al., 2009). In another study with melon, an improvement in *WUE* was obtained by increasing the N level to 120 kg ha^{-1} of N_{av}, due to increased yield (Kirnak et al., 2005). Low N supply will not only result in lower yield but will also reduce *WUE* (Brück et al., 2001). High N levels can reduce yield due to excess water use in the pre-anthesis period, leaving insufficient water post-anthesis (van Herwaarden et al., 1998).

The highest values of *DWUE* and *DIRRWUE* were in the treatments which gave the greatest *DW*. In 2005, both efficiencies were

Table 2
Water use efficiency, based on fruit yield (*FY*) and dry weight (*DW*) with respect to *ETc* and *Irr*, in the melon crop in 2005, 2006 and 2007.

	Treatment	*WUE* (kg m^{-3})	*IRRWUE* (kg m^{-3})	*DWUE* (kg m^{-3})	*DIRRWUE* (kg m^{-3})
2005	N_{122}	8.6 a	6.7 a	1.3 a	1.0 a
	N_{176}	10.4 ab	8.2 ab	1.9 ab	1.5 ab
	N_{200}	11.0 b	8.6 b	2.2 b	1.7 b
	N_{219}	9.6 ab	7.5 ab	2.1 b	1.7 b
2006	N_{156}	10.0 b	7.6 b	1.8 a	1.4 a
	N_{314}	9.1 b	6.9 b	1.7 a	1.3 a
	N_{461}	7.7 a	5.9 a	1.7 a	1.3 a
2007	N_{47}	9.7 a	7.1 a	1.7 a	1.2 a
	N_{91}	11.0 ab	8.0 b	2.0 ab	1.4 ab
	N_{124}	12.1 bc	8.8 bc	2.2 bc	1.6 bc
	N_{188}	12.6 c	9.2 c	2.3 c	1.7 c

For each year and within each column, values followed by the same letter are not different ($p \leq 0.05$).

improved by 40, 59 and 61% with 176, 200 and 219 kg N ha^{-1}, respectively, compared to 122 kg N ha^{-1}. In 2006, N had no effect on the efficiencies. In 2007, the efficiencies obtained with 47 kg N ha^{-1} were increased by 34% at 188 kg N ha^{-1}. A close relationship between *WUE* and *DW* in tomato crop was observed (Claussen, 2002).

4.4. Environmental indexes

If all three years of data are considered, the relationship between *II* and N_{av} showed a highly significant, linear regression ($R^2 = 0.92$) (Fig. 4). Treatments giving $Nitrate_{leachate}$ in excess of 50 mg L^{-1} will have an $II > 1$ and will be located above the horizontal dotted line, while those treatments in which $Nitrate_{leachate}$ is below this threshold will have an $II < 1$ and will lie below the horizontal line.

The treatments which gave leached nitrate concentrations exceeding 50 mg L^{-1} were N_{200} and N_{219} in 2005, N_{314} and N_{461} in 2006 and N_{188} in 2007. The other treatments gave concentrations which were beneath the maximum allowable value. For the optimal dose of 160 kg ha^{-1} N_{av}, *II* was 0.99. This approach is an effective tool for determining whether agricultural practices pose a risk to the use of groundwater as drinking water. It is desirable and required not to exceed the maximum allowable nitrate concentration.

The *EII* showed a highly significant, linear regression in relation to N_{av} ($R^2 = 0.89$) (Fig. 5). All treatments with leached nitrate concentrations exceeding the nitrate concentration of the groundwater have an *EII* value greater than 1 and will be located above the horizontal dotted line, located at an *EII* of 1, while those treatments in which the concentration of leached nitrate was less than that of the groundwater have a management impact index below 1 and will lie below the horizontal line.

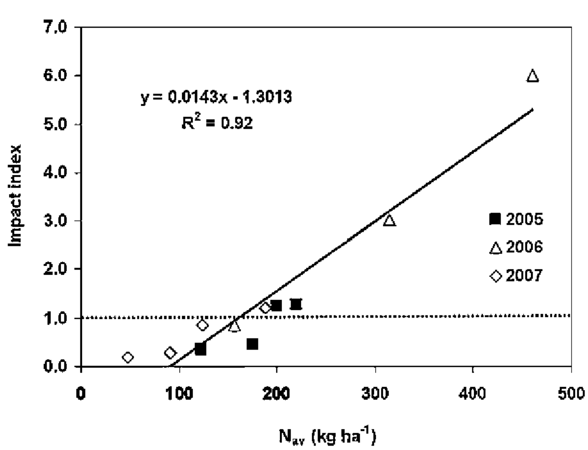

Fig. 4. Impact Index (*II*) versus N available (N_{av}). Discontinuous lines correspond to the maximum limit, when the concentration of the NO_3^- leaching is 50 mg L^{-1} – equal to the maximum concentration established for drinking water.

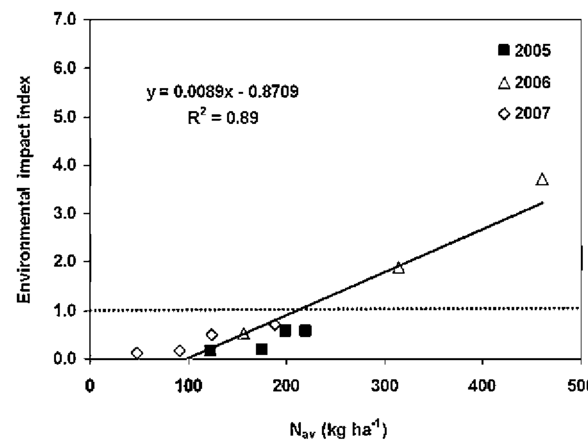

Fig. 5. Environmental Impact Index (*EII*) versus N available (N_{av}). Continuous lines show when the concentration of the NO_3^- leaching is equal to the concentration of NO_3^- in the groundwater.

The only treatments that showed an *EII* greater than 1 were N_{314} and N_{461}, because in our study conditions the high concentration of nitrate in the groundwater means that it is already contaminated.

The *EII* approach is a practical tool for quantifying the risk of groundwater contamination due to N application.

The *ME* represents the amount of fruit produced per gram of N_l. The results show that if N_{av} was increased, *ME* was reduced – so the amount of N_l was higher and *FY* declined (Fig. 6). For the optimal dose of 160 kg ha^{-1} of N_{av}, *ME* was 7.4 kg FY g $N_l$$^{-1}$.

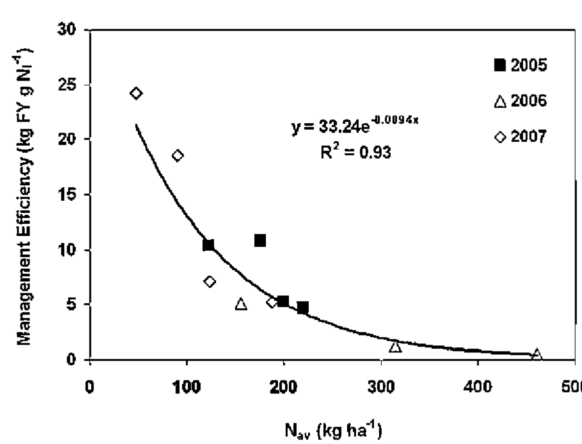

Fig. 6. Management Efficiency (*ME*) versus N available (N_{av}).

Table 3
N uptake (N_{up}), N leaching (N_l), soil mineral nitrogen to the end of the crop cycle (N_s *final*), N Mineralization (*NM*), N Mineralization daily (*NM daily*) and N uptake efficiency ($N_{up}E$) in 2005, 2006 and 2007.

	Treatment	N_{up} (kg ha^{-1})	N_l (kg ha^{-1})	N_s *final* (kg ha^{-1})	*NM* (kg ha^{-1})	*NM daily* (kg ha^{-1} day^{-1})	$N_{up}E$ (%)
2005	N_{122}	77.3 a	3.9 a	128.3	87.4 c	0.8 c	36.8 a
	N_{176}	127.9 ab	4.6 a	124.1	80.9 bc	0.7 bc	49.8 b
	N_{200}	178.4 bc	9.9 b	91.6	79.9 b	0.7 b	63.4 c
	N_{219}	188.6 c	9.6 b	87.9	67.0 a	0.6 a	65.4 c
2006	N_{156}	142.7 a	8.1 a	59.7	54.5 c	0.5 c	67.5 b
	N_{314}	163.1 a	31.3 b	167.9	48.2 b	0.5 b	45.5 a
	N_{461}	167.5 a	59.6 c	259.7	26.3 a	0.2 a	39.1 a
2007	N_{47}	82.6 a	1.5 a	87.9	124.6 c	1.2 c	48.3 a
	N_{91}	113.3 ab	2.1 a	104.1	128.7 bc	1.2 bc	52.3 ab
	N_{124}	138.1 bc	7.0 b	97.6	119.0 b	1.1 b	56.3 bc
	N_{188}	165.0 c	8.6 b	104.8	90.2 a	0.8 c	59.3 c

For each year and within each column, values followed by the same letter are not different ($p \leq 0.05$).

4.5. Nitrogen mineralisation

To calculate the *NM*, it was necessary to consider all the parameters needed for the N balance of Eq. (7). The N_{up} rose with increasing addition of N, except among the treatments in 2006 where there were no significant differences (Table 3).

The N_l increased exponentially with the amount of N_{av} (Fig. 7) ($R^2 = 0.90$). The greatest loss of N_l occurred with treatment N_{461} (59.6 kg ha^{-1}) and the smallest with N_{47} (1.5 kg ha^{-1}) (Table 3). The use of a greater amount of N results in a higher possibility of nitrate formation in the soil and subsequent leaching to aquifers increases (Kundu and Mandal, 2009).

The N_s *final* was higher than the N_{av} at the beginning of the crop cycle in treatments N_{122}, N_{47} and N_{91}, which means that N mineralisation in these treatments was more evident and higher than for the other treatments (Table 3). In the other treatments, the value of this parameter was lower than that of N_{av}.

The *NM* ranged between 26.3 (N_{461}) and 128.7 (N_{91}) kg ha^{-1} (Table 3). A relationship between *NM* and N_{av} was obtained (Fig. 8): with higher N_{av}, *NM* was decreased exponentially ($R^2 = 0.85$). For the optimal dose of 160 kg ha^{-1} of N_{av}, *NM* was 85 kg ha^{-1}. Similar results were found in the literature, regarding a detectable effect of fertiliser N on readily mineralisable N in the plough layer (Bremer and Kuikman, 1997; Silgram and Chambers, 2002). A sufficient amount of fertiliser N stimulated formation of the biologically active pools of N (biomass N and active N) in soils under no-tillage treatments, but the excessive use of fertiliser N tended to suppress these pools (McCarty and Meisinger, 1997). There are indications that some microorganisms have a "luxury uptake" of N when it is present in sufficient amounts, thereby delaying N mineralisation (Fog, 1988).

The *NM daily* was calculated considering the *NM* and the number of days elapsed (Table 3). The *NM daily* ranged between 0.2 kg ha^{-1} day^{-1}, for N_{461}, and 1.2 kg ha^{-1} day^{-1}, for both N_{47} and N_{91}.

In more-intensive agricultural systems, fertiliser inputs make up a significant component of the N balance. This means that limiting the nutrients applied to farmland should improve local water quality, sooner or later. Fertiliser application is becoming more precise (location, timing, amount) as farmers account better for other sources of nitrate in the soil and tailor applications to specific crop needs. This should decrease the amount of excess nitrate in the soil that is available for leaching to surface or groundwater (Burt et al., 2010). Nitrate leaching occurs when there is an accumulation of nitrate in the soil profile, either in excess of crop needs or between crops, which coincides with or is followed by a period of high D (Di and Cameron, 2002). The N mineralisation is important in the N balance: knowledge of this parameter permits a better match between the available N and crop needs, thus reducing nitrate leaching (Dinnes et al., 2002).

If all three years of data are considered, the relationship between the N Mineralisation Index (*NMI*) and N_{av} is highly significant, fitting an exponential regression ($R^2 = 0.95$) (Fig. 9). This means that as N_{av} increased, the *NM* decreased exponentially.

4.6. N uptake efficiency

Increasing N availability ($N_{av} + NM$) increased $N_{up}E$ from 36.8 (N_{122}) to 65.4% (N_{219}) in 2005 and from 48.3 (N_{47}) to 59.3% (N_{188}) in 2007; but, in 2006, the opposite occurred – the efficiency decreased

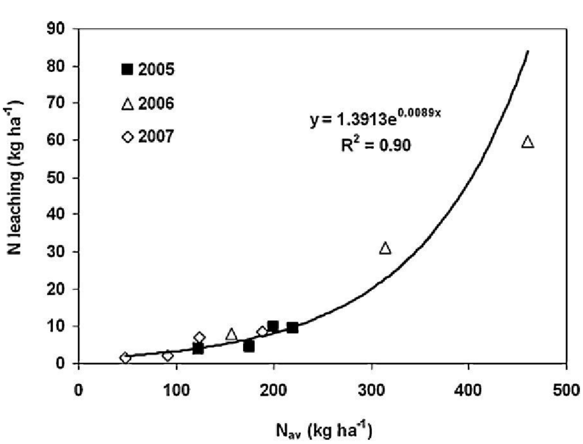

Fig. 7. Nitrogen leaching (N_l) versus N available (N_{av}).

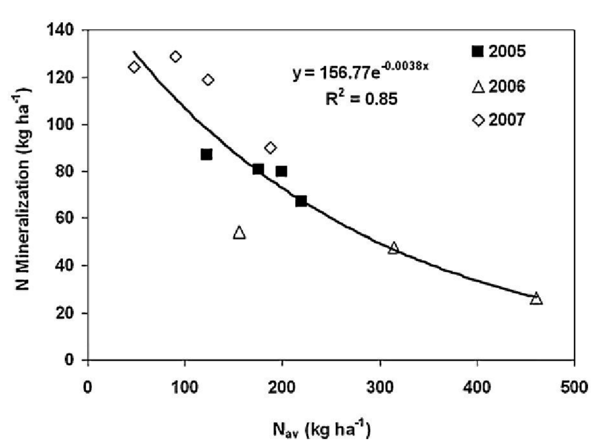

Fig. 8. Nitrogen mineralisation (*NM*) versus N available (N_{av}) in 2005, 2006 and 2007.

Table 4
Matrix of correlation: Impact Index (*II*), N Mineralization (*NM*), N Mineralization Index (*NMI*), Environmental Impact Index (*EII*). Management Efficiency (*ME*), Irrigation Water Use Efficiency in relation to FY (*IRRWUE*) and in relation to *DW* (*DIRRWUE*), Water Use Efficiency in relation to *FY* (*WUE*) and in relation to DW (*DWUE*), N Uptake Efficiency ($N_{up}E$) and *Relative FY*.

	II	NM	NMI	EII	ME	IRRWUE	WUE	DWUE	DIRRWUE	$N_{up}E$	Relative FY
II	1.00										
NM	−0.76**	1.00									
NMI	−0.52	0.80**	1.00								
EII	1.00***	−0.74**	−0.49	1.00							
ME	0.99***	−0.73**	−0.46	0.99***	1.00						
IRRWUE	−0.57	0.52	0.05	−0.58	−0.64*	1.00					
WUE	−0.54	0.60	0.16	−0.54	−0.60*	0.98***	1.00				
DWUE	−0.16	0.23	−0.13	−0.19	−0.27	0.81**	0.80**	1.00			
DIRRWUE	−0.15	0.12	−0.24	−0.19	−0.26	0.77**	0.72*	0.98***	1.00		
$N_{up}E$	−0.44	0.14	−0.09	−0.48	−0.53	0.68**	0.62*	0.74**	0.77**	1.00	
Relative FY	−0.26	−0.02	−0.40	−0.27	−0.34	0.79**	0.72*	0.69*	0.70*	0.75**	1.00

* Significant coefficient: at 95% confidence ($p < 0.05$).
** Significant coefficient: at 99% confidence ($p < 0.01$).
*** Significant coefficient: at 99.9% confidence ($p < 0.001$).

with increasing N (Table 3). This is because the N was taken up quickly until N_{av} was approximately 300 kg ha^{-1}; above this amount, the N_{up} remained constant at a maximum of 180 kg ha^{-1} (Castellanos et al., 2010b).

4.7. Relationship between environmental indexes and efficiencies

There are relationships among the environmental indexes and efficiencies determined in this study. In Table 4, the matrix correlation coefficients obtained are shown, as well as their significances. The strongest correlations were obtained for *ME* and *WUE* with *FY* (*IRRWUE* and *WUE*), followed by *WUE* with *DW* (*DWUE* and *DIRRWUE*), $N_{up}E$ and *Relative FY*, then *NM* and the environmental indexes (*II* and *EII*); finally, *NMI* showed the weakest correlations. Based on this, several variables were selected to try to capture the maximum information with the minimum number of efficiencies and indexes. The following variables were selected, avoiding high correlations: crop yield (*Relative FY*), water use (*IRRWUE*), N use ($N_{up}E$) and contamination (*II*, *ME*). Although different treatments were compared in an integrated way, a radial representation was achieved (Fig. 10).

The *IRRWUE*, $N_{up}E$ and *ME* values have previously been normalised, to minimise the influence of variation range in their representation. In the case of *II*, based on the existing DWD, any value greater than 1 has been awarded a value of 0, since this agricultural practice poses a risk of pollution. In the remaining cases, to arrange the index so that "more is better", it is shown as $II' = 1 - II$.

Different treatments were compared in each year. In 2005 (Fig. 10A), N_{200} and N_{219} had the highest pollution risk, differing

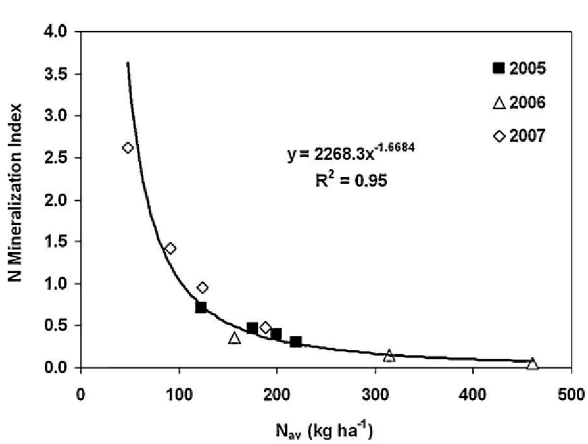

Fig. 9. Nitrogen Mineralisation Index (*NMI*) versus N available (N_{av}).

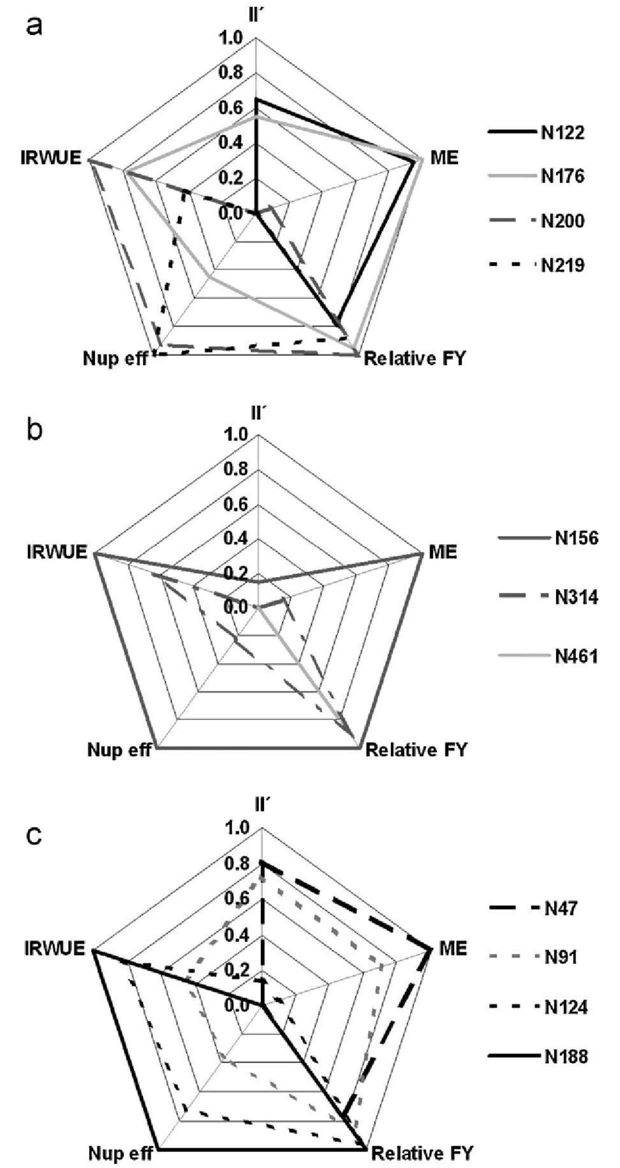

Fig. 10. Radial representation of *IRRWUE*, $N_{up}E$ and *ME* (previously normalized) and II′, calculated as $II' = 1 - II$, in 2005 (A), 2006 (B) and 2007 (C).

in their *IRRWUE*. However, N_{176} was the most-efficient treatment, with the lowest pollution risk. In 2006 (Fig. 10B), N_{156} was the most efficient, with the exception of II′, although $Nitrate_{leached}$ did not exceed 50 mg L^{-1}. With an excessive N availability, N_{314} and N_{461} not only caused contamination of the drainage water, but had lower yields and *IRRWUE*. This was due to a combination of two factors: firstly, the water used was groundwater (used by farmers in the area), with a high concentration of nitrate, and secondly, the high overdose of N_{ap}.

In 2007 (Fig. 10C), two different behaviours were observed: low N doses (N_{47} and N_{91}) gave a good environmental performance and less-productive efficiency, whereas higher N doses (N_{124} and N_{188}) gave good *IRRWUE*, $N_{up}E$ and *Relative FY* but a higher environmental risk.

5. Conclusions

The results showed that the highest yields were obtained with a dose of about 160 kg ha^{-1} of N_{av}, being at the same time the maximum *WUE*. Doses higher than this had negative effects on yield and WUE; in addition this overdose increased exponentially the loss of nitrate leaching. This effect was observed with the ME, which represents the kg of fruit produced per g of N_l.

The N_{av} negatively affected the mineralisation of N. For optimal dose of 160 kg ha^{-1} of N_{av}, N mineralisation was 85 kg ha^{-1}.

The proposed environmental indexes proved to be effective for determining the risk of nitrate contamination according to the N applied, and should be promoted in future BMP to reduce nitrate contamination in aquifers through optimised management of inorganic N fertiliser.

The methodology employed in this study allowed us to evaluate the optimum fertigation management, by integrating both economic and environmental aspects. Given the complexity of the system, we have simplified the number of indexes and efficiencies needed to establish the framework of N management and its economic and environmental consequences.

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